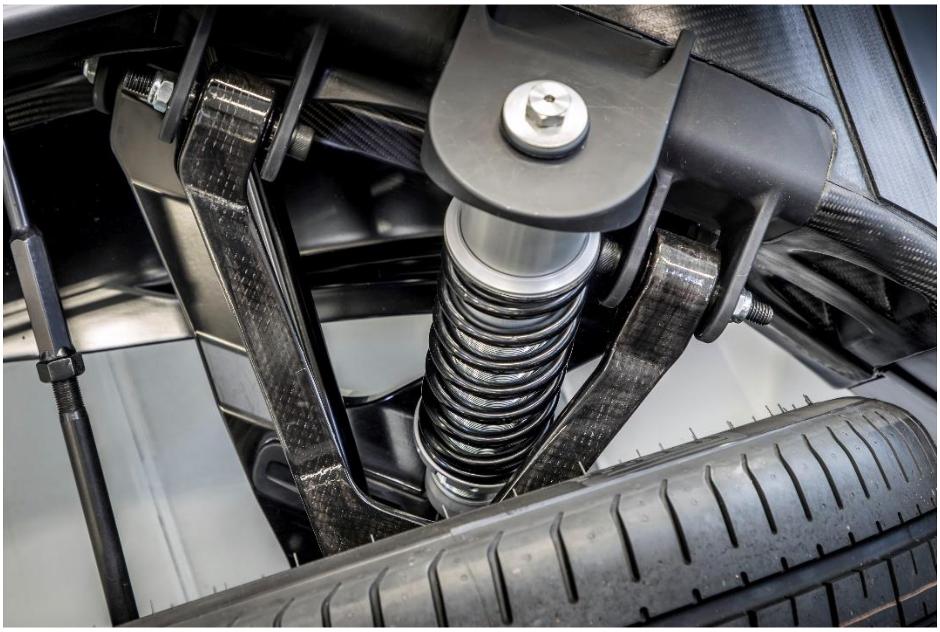
A new approach to the
manufacture, application and recovery of

Carbon Composite Structures



Innovations for
strength, weight reduction, ease of manufacture

automotive, aerospace, off-shore, rail, renewable energy

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INTRODUCTION

Challenges and Opportunities

Carbon fibre reinforced polymer (CFRP) is a material of huge promise. Its exceptionally high strength-to-weight ratio, impressive stiffness and excellent fatigue and environmental resistance make it an attractive choice for a wide variety of industries and applications.

This is particularly pertinent to the automotive industry, where lightweighting is seen as one of the primary tools needed to meet increasingly stringent fuel economy and emissions targets, as well as support the range required from electric vehicles. However, the advantages of CFRP extend across many sectors, from railway carriages to wind turbines.

Despite these compelling benefits, and recent process advances from the automotive and aerospace industries, a number of factors have held back the mass adoption of CFRP. Chief among these is cost, with traditional composite production methods involving expensive materials and lengthy process times. They also incur a relatively high scrap rate (typically around 30 per cent), compounded by the challenges of recovering the carbon from pre-impregnated off-cuts, and of finding value from the material at the end of the product life.

These challenges have seen the application of CRFP largely confined to niche applications. In the automotive sector, for instance, a body-in-white structure produced with traditional composite techniques is typically around 60 per cent lighter than one manufactured in steel, yet around 20 times the cost[(1)]. This has limited its application to vehicles that are low volume / high cost, or where the vehicle manufacturer subsidises the process as part of their learning around new technologies.

"In the automotive sector, lightweighting is one of the primary tools needed to meet increasingly stringent fuel economy and emissions targets"

Williams Advanced Engineering has developed a pair of innovative technologies that promise a step-change in the affordability of composite materials. Known as 223™ and Racetrak™, these technologies offer comparable performance to existing composites solutions, but with a range of additional benefits, and at a cost that brings them within reach of mainstream applications. These are not simply manufacturing innovations: they are end-to-end, whole-life solutions that address every aspect of the manufacture, use and recycling of CFRP and the way in which its remarkable properties can enable new approaches to vehicle design and manufacture.

This White Paper explains these innovations and the benefits that they bring.

WILLIAMS ADVANCED ENGINEERING - A CULTURE OF INNOVATION

Williams Advanced Engineering Limited operates a technology and engineering services business and is part of the Williams Group. In 2010, Williams Grand Prix Engineering Limited began diversifying its operations, leading to the establishment of the Williams Advanced Engineering division, which has now become Williams Advanced Engineering Limited. Building on four decades as one of the world's most successful Formula 1® constructors, with 16 FIA Formula 1 World Championship titles, the company has a deeply ingrained culture of quality, rigour and relentless innovation. Combining cutting edge technology and the industry's best engineers with precision and speed to market derived from four decades of success in the ultra-competitive environment of Formula One, Williams Advanced Engineering provides world class technical innovation, engineering, testing, manufacturing and operational consultancy services across all sectors of industry. Working in close collaboration with its customers, Williams Advanced Engineering helps meet the sustainability challenges of the 21st century and improve performance, with its expertise in aerodynamics and thermodynamics, electrification, advanced lightweight materials, simulation and vehicle integration. The company was honoured with the Queen's Award for Enterprise in Innovation 2018.

To encourage its engineers to put forward new ideas, Williams Advanced Engineering has developed a system that supports innovation, providing expertise and resources to develop and commercialise ideas with the inventor having a stake in the product. Both 223™ and Racetrak™ have benefitted from this scheme, demonstrating the value that comes from investing in the very best people and giving them an environment where creativity is not just encouraged, but is proactively supported. A significant level of profits is invested in Williams' own R&D, transforming the business from a Formula 1 team with a highly successful consulting division, to one that also owns substantial intellectual property that will be of great value to a wide range of industries that require energy efficient, high-performance technologies.

"Racetrak™ and 223™ are just two examples of this new generation of technologies, developed and commercialised by Williams Advanced Engineering," says Chief Technology Specialist, Lightweight Structures Iain Bomphray, the Williams Advanced Engineering innovator behind these two breakthroughs. "With this approach, we have the potential to develop new, growing areas of business that will also make significant contributions to the industries in which we work."

The Williams Advanced Engineering FW-EVX™ is a vision of a future electric vehicle platform that integrates a range of new approaches, including Racetrak™ and 223™, into a single, highly integrated solution that addresses the challenges of effective, affordable electric vehicles.

"We are focussing our expertise on energy management, aerodynamics, thermodynamics and lightweighting. As tools for efficiency improvement, these are all highly synergistic, so considering them as an integrated system allows us to increase significantly the total benefits," explains Williams Advanced Engineering Technical Director Paul McNamara. "While we have undoubtedly learnt a great deal from success in Formula 1 and Formula E, they are high-profile examples of what we do. Behind closed doors, we are solving challenging problems for world-class companies across a wide range of sectors and working with some of the most highly-regarded manufacturers on next-generation, low carbon technologies."

Vehicles developed with expertise from Williams Advanced Engineering already include the Nissan BladeGlider, the Jaguar CX-75 hybrid supercar and the Aston Martin Rapide E. Outside the automotive industry, Williams Advanced Engineering already manufactures products such as the light weight Babypod 20 that is saving young lives and the Core Infrastructure Distribution System for General Dynamics' Scout Specialist Vehicle for the British Army, designed and industrialised by its world-class innovators.

223™ ™ - A NEW DIMENSION IN COMPOSITE STRUCTURES

Enabling a New Approach to Manufacture and Assembly

The 223™ process was conceived as a cost-effective means of creating three dimensional composite structures from a two-dimensional form. It is ideal for box-like geometries, such as battery containers for electric vehicles, or potentially even complete vehicle monocoques.

The name is derived from one of the process's defining features: while composite components generally have to be laid up in their final geometry, 223™ allows the part to be created initially as a two-dimensional component before being folded into a three-dimensional structure.

This lends itself to a wide array of applications. In particular, 223™ suits structures that are currently assembled from many separate components, and where access for fitting-out adds time and cost. A good example is an automotive body-in-white, which typically consists of around 300 metal pressings, made with perhaps 600 different tools; a vehicle bonnet may require four different press operations. Using 223™, the number of pressings could be reduced to around 50, all created on a single machine with a significant reduction in the capital expenditure for tooling.

It is estimated that a weight saving of around 25 to 30 per cent could be achievable on a car's body-in-white, compared to an equivalent aluminium alloy structure. With 223™, this could be delivered in higher volumes and at a lower cost than a traditional composite solution. Where less strength is required, further cost savings could be made by specifying lower cost materials, for example glass fibres, while alternative resins can be specified to increase toughness and heat resistance.

The Williams Innovation

The heart of the 223™ innovation is a radically different (and therefore confidential) process for the integration of woven, dry fibre reinforcement sheet with a separately-prepared resin matrix. The technique provides unprecedented freedom to optimise both elements to the specific requirements of a design across the component. For example, a design may employ high-strength carbon fibres as the reinforcement in structurally critical areas, while low cost glass fibres could be used in others. Costly materials are used only where their benefit is required, and local strength can be provided without the cost of additional reinforcing components. The process enables the full benefits of the anisotropy of the material to be exploited, as apposed to a 'black metal' approach.

The process begins with an automated cutter trimming the flat sheet of woven fibre into near-net shape. The excess material from this process is dry, untreated fibre, which is substantially easier and more cost effective to recycle than traditional pre-impregnated materials. At this stage, other components can be easily embedded, such as printed electronics and energy absorbing materials.

Next, the matrix is applied using an automated process that allows the composition of the resin to be specified locally across the part, allowing properties such as toughness and thermal conductivity to be varied across the component. At this stage, the preform is still a flat, two-dimensional sheet, like a cardboard box that has yet to be folded.

Williams Advanced Engineering estimates fibre deposition rates of up to 500 kg per hour. Overall, including other areas of process time saving, 223™ is up to around 50 times faster than traditional aerospace-grade methods, which lay down material at roughly 10 to 20 kg per hour.

The preform is then fed into an industrial press, where a carefully-controlled force and temperature is applied. This cures the sections that are destined to form the faces of the box, while leaving the hinge areas between them flexible. Thanks to snap curing resins, the pressing process can be accomplished in around three minutes and with a high degree of automation. Energy, cost and time savings are also evident from the ability to maintain the press at a constant temperature, where otherwise the autoclave or press would traditionally go through a temperature cycle, adversely affecting the operational efficiency. Again, a further benefit of the process.

Once removed from the press, the cured areas have sufficient structural strength for additional manufacturing steps to be performed. 223™ has been designed to allow transportation of the product to an external facility in this intermediate ‘flat pack’ form, potentially reducing the cost of logistics. In a defence vehicle application, for example, vehicle bodies could be kept flat in storage, with the correct body for the requirement selected and dispatched quickly and efficiently for assembly in the field.

Components can be held in this intermediate ‘flat pack’ form for relatively extended periods (up to 12 months) – currently days, with extended times in development - allowing complex tasks to be performed before the final curing stage is carried out. For instance, on an automotive body-in-white, it could potentially provide scope to fit trim, run electrical / electronic harnesses and install heating ventilation and cooling (HVAC) components with easier, faster access and fewer additional tools.

Finally, the part is placed in a jig, where it is folded into its finished three-dimensional form. It then undergoes a final curing stage, which solidifies the hinges and seamlessly joins the edges of the adjacent panels to create a perfect three-dimensional shape.

Efficient, Cost-Effective Recycling

As well as being highly efficient and enabling new approaches to logistics and assembly, the 223™ process is also environmentally attractive. Conventional techniques (such as autoclave) for manufacturing components in CFRP typically result in upwards of 25 per cent scrap because when pre-impregnated (fibres supplied already embedded in resin) it is uneconomic to recycle. Extracting the fibres requires a complex procedure to separate them from the resin, typically involving pyrolysis or solvolysis chemical decomposition, which consumes energy, incurs additional cost and increases the process’s overall carbon footprint.

Because off-cuts from the 223™ process are dry, without resin around the fibres, they can be simply fed into a carding machine (a drum with internal spikes in which the recyclate is tumbled). This allows them to be easily converted into a felt-like non-woven material with carbon fibres a few millimetres long. The random direction of the fibres means the recovered material is not suitable for high-strength applications, but the toughness, lightweight and acoustic damping characteristics make it ideal for applications such as door casings and instrument panels or as a core within a laminate to improve noise, vibration and harshness (NVH) benefits, damage tolerance and structural strength.

RACETRAK™ - MAKING HIGH-STRESS COMPOSITES AFFORDABLE

Changing the Way Composites Are Manufactured

Racetrak™ is a novel process for creating very high strength structural members that link two or more points, such as automotive wishbones or the link arms of aircraft landing gear. The technique draws on a proven design concept, where a continuous loop of unidirectional material - in this case carbon fibre - provides extremely high hoop strength. This localisation of very high embedded strength allows substantial cost reduction which, when combined with high levels of automation, allows an affordable component that is dramatically lighter than traditional alternatives.

In the case of a wishbone for an automotive application, the finished part could be around 40 per cent lighter than the equivalent forged aluminium item and up to 60 per cent lighter than steel, making it cost-competitive with a premium aluminium forging. This puts it in line with the automotive industry's budget for weight saving technologies, estimated at €5 to €7 per kg in a recent report by McKinsey & Company.(4)

Up to 80 per cent of the material can be drawn from recycled sources, helping to solve the growing challenge presented by end-of-life carbon composite components.

The Williams Innovation

The Racetrak™ parts consist of three main components: a core of low cost, non-woven bulk material, a loop of unidirectional carbon fibre and on both sides of this, a protective shell made from die-cut woven fibre sheet. Manufacturing is fully automated, with the unidirectional loop robotically wound to create precise, repeatable tailored fibre placement. This reinforced material preform is then placed dry into a tool, which applies a light shaping pressure to create a removable cartridge.

This is placed into an industrial press, where a vacuum is applied and the resin is injected into the heated mould. Under these conditions, the resin takes approximately 90 seconds to cure. It is then ejected from the machine and a fresh cartridge loaded.

"An automotive wishbone could be around 40 percent lighter than an equivalent forged aluminium component **and up to 80 per cent lighter than steel"**

With a cycle time currently at just 120 seconds, a single press using this process can produce more than 500,000 units a year. The composition of the system also contributes to an attractive price / performance ratio as the most costly materials – notably the unidirectional carbon fibre – are used only where their unique mechanical properties are required to deliver high local strength, for example to link anchorage points. The woven shell increases load distribution across the component and enhances both sheer strength and damage tolerance.

The system allows a choice of resins, for example polyurethane instead of the more conventional epoxy resin, increasing the toughness of the system as well as reducing the cost, with the option to further increase energy absorption by adding ductile materials such as ground end-of-life CFRP. Polyurethane resin is also an effective adhesive, allowing in-mould integration of fixings and other components. For increased resistance to high temperatures, a phenolic resin could be specified.

The Racetrak™ process takes its name from the continuous loop of fibre around the load bearing area, said to resemble a race track when viewed from above. For maximum strength, carbon fibres are specified for this loop, but other fibres could be used. Fibres such as glass could be incorporated in the resin matrix to provide additional strength and toughness.

Efficient Manufacturing

As with the new 223™ process, automation ensures repeatability, removes the need for skilled labour, reduces cycle times and minimises the quantity of premium material that is required for unidirectional lay-up. Each tool costs around one tenth the cost of a steel tool, making smaller production runs more affordable. The same tool can also make similar shaped components of different specifications, simply by changing the composition of the cartridge.

Williams Advanced Engineering proposes that with savings in process time, skilled labour, materials and capital investment, Racetrak™ will allow high strength, light weight composite components to be used in applications where CFRP was previously too costly.

Like 223™, Racetrak™ also brings additional benefits, most notably the ability to embed components such as thin film sensors (which can be just 6 µm thick) and bearings, effectively removing another step from the current production process. Thin film sensor could, for example, be used to measure torque or to identify internal failures resulting from out of tolerance stress.

Racetrak™ is also environmentally attractive because it requires very little energy, and because the bulk material used in the core can be created from the multidirectional carbon created from the 223™ and Racetrak™ manufacturing scrap (see above). It can also use a high proportion of ground material created from end-of-life recyclate, helping to solve the current challenge of how to recover and re-use carbon components from end-of-life vehicles as required by legislation, such as the European End-of-Life Directive.

APPLICATION AREAS

Racetrak™ and 223™ ™ are both application-agnostic. Their inherent scalability and adaptability lend them to a wide variety of different functions and applications. However, Williams Advanced Engineering has identified three sectors where these techniques could bring particular benefits.

Automotive Including Commercial & Off-Highway Vehicles

The automotive industry is perhaps where the biggest gains are to be had from the use of CFRP. According to McKinsey & Company(4), the market share of lightweight materials such as CFRP and aluminium is expected to grow from 30 per cent to 70 per cent by 2030. CFRP's share of this market is forecast to grow substantially, driven by increased lightweighting requirements and by the arrival of production processes that are more affordable in volume production.

There is a very close correlation between vehicle weight and emissions, with studies indicating that a 10 per cent reduction in vehicle weight can result in a 6 to 8 per cent improvement in fuel economy(2). As of 2021, the European Union has set a stringent fleet-average CO_2 target of 95 g/km for all manufacturers. The penalty for failing to meet these targets is severe – €95 for each gram of CO_2 on every car above the limit. In the UK, the average new passenger car currently emits just over 120g/km(3), which would equate to a €2,375 burden on the cost of each car if that figure was to be carried through to 2021. And this may just be the tip of the iceberg. A revised EU target is due for 2025, which is expected to be as low as 75 g/km.

Despite the focus on emissions reduction, there is still a marked trend towards larger, better equipped vehicles with higher energy consumption. Consumers want added space, more sophisticated comfort and infotainment functions, greater crashworthiness and a growing range of advanced driver assistance systems (ADAS); all of which adds weight. It is not simply a case of saving weight from where we are today: if lightweighting technologies failed to progress at increasing speed, weight would continue to increase.

Take low carbon powertrain technologies as an example. A plug-in hybrid powertrain can add approximately 150 kg to the total weight of a vehicle, while a battery electric hybrid can be 250 kg more than its internal combustion-only counterpart(4). Even pure electric vehicles with kinetic energy recovery are extremely sensitive to weight, which is why BMW has invested in a carbon structure to increase the performance and range of its i3 electric vehicle.

One of the prime candidates for weight reduction is the vehicle's body-in-white, a key area where the 223™ process could offer significant benefits. Williams estimates that a vehicle monocoque produced in carbon composite using their 223™ process could be 25 per cent lighter than an aluminium structure with comparable attributes.

Williams Advanced Engineering has already employed this process in the production of the battery case for its FW-EVX™ Electric Vehicle Platform concept, providing a lightweight, yet strong and highly crashworthy structure(8).

FW-EVX™ also highlights one of the potential automotive applications of Racetrak™, which was used to manufacture the suspension wishbones with a weight saving of approximately 40 per cent compared with aluminium and 60 percent compared with steel. Lighter wishbones reduce unsprung mass, which also improves vehicle dynamics and ride quality, while the component's stiffness can improve turn-in and steering feel.

Williams Advanced Engineering has designed and manufactured composite wishbones for its Formula 1 cars for more than 25 years, giving it considerable experience in this application. In road car applications, a composite wishbone could weigh as little as 500 g. Using the technique to manufacture the lower control arm with an integrated MacPherson Strut mounting could save an additional 2 kg per corner, potentially saving 10 kg per vehicle compared with the aluminium equivalent.

Proven design tools and simulation methods are available, so it should be relatively easy for vehicle engineers to introduce these new techniques as direct materials substitution, before progressing to introduce further benefits as vehicle designs evolve.

"A structure manufactured using 223 could be 25 percent lighter than an aluminium structure with comparable attributes"

Automated Driving Fuels the Need for Composites

Looking ahead, the trend towards automated driving could also fuel the need for affordable composites in the automotive sector. Not only does this bring yet more mass and substantially more energy consumption to offset, it also begs the question of how this technology will be integrated into the platform. The use of composite processes such as 223™ and Racetrak™ bring the prospect of more flexible design, while both these technologies support the use of embedded thin film sensors.

One possibility is turning wishbones and other CFRP components into calibrated load cells that could transfer road load data back to the vehicle via wireless electronics. This would not only allow a vehicle manufacturer to capture anonymised usage data, it will also have practical applications at a vehicle level, measuring real-time loads applied to a component. An example is a wishbone providing data that can be used to infer lateral grip, for use by the stability control input.

Increasing Efficiency for Heavy Duty and Off-Highway Vehicles

In the commercial vehicle sector, weight saving can translate directly into revenue from additional payload and savings from improved fuel economy. When metropolitan authorities are placing increasing importance on vehicle emissions, the increased efficiency brought by light weighting can also help operators comply with tough local pollution requirements.

In the Off-Highway sector, weight can be the friend of the designer because of the stability it brings, but that does not make efficiency any less important. Affordable carbon composites allow engineers to save weight where it will make the biggest difference, for example in reciprocating components like stacker forks, or where it compromises stability such as high on crane masts.

Aerospace

It was the aerospace industry that pioneered the use of composite technologies in the 1960s and the sector remains at the forefront of their adoption. In recent years, the Boeing 787 Dreamliner and Airbus A350 XWB have become the first commercial aircraft where lightweight composites account for a majority of the structure. Production volumes, however, allow for low cycle times: according to Bloomberg,[5] Boeing expects to build 14 Dreamliners each month.

Composites are an attractive option in aerospace for much the same reasons as they are in automotive: regulatory and commercial pressures on both emissions and fuel consumption. As well as increasing emissions, every additional kilogram of mass carried into the air increases the cost of operating the aircraft and reduces the payload weight available for paying passengers and cargo.

The International Air Transport Association (IATA) has vowed to halve the industry's emissions by 2050. A recent study concluded that the global transition of aircraft to composite structures would contribute 20 to 25 per cent towards that target[6]. The same investigation found that the lifecycle CO_2 production of an aircraft with a composite fuselage – including the complete manufacturing supply chain and its eventual disposal – could be 20 per cent less than an aircraft with an equivalent aluminium structure.

"The global transition of aircraft to composite structures would contribute 20 to 25 per cent towards IATA's 2050 emissions target"

With the largest airliners now containing over 600 seats, in-cabin weight reduction is a particularly key area for lightweighting. Williams Advanced Engineering's 223™ process lends itself to the production of seat sections, while Racetrak's load-carrying capabilities make it a compelling option for lightweight seat rails and other components, including wing spars, where a clear load path is required to ensure safety requirements are met. Elsewhere on the aircraft, other potential applications include wing flap actuators and links and swing arms in landing gear.

One of the traditional challenges with the adoption of composites in such a highly regulated environment has been how to assess damage, especially from fatigue. This is an area where the aerospace industry has already taken great strides with non-destructive testing techniques for carbon composites now well understood. The ability to embed electronics such as load cells into components will take this a step further. For example, it will be possible to wirelessly interrogate each component on the history of its mechanical loadings to determine its remaining cycle life, potentially extending the life of components through improved data.

Renewable Energy

The excellent strength-to-weight of composite materials makes them an ideal choice for any large, rotating component. Wind turbine blades are perhaps the largest of them all, with some individual blades now more than 80 metres from hub to tip. It is largescale turbines (those blades over 40 metres) that are expected to see the most pronounced increase in the use of composite materials. With the output of wind energy expected to more than double between 2020 and 2030[7], this is a substantial market that could see significant benefits from the new techniques.

Much like any other composite structure, there is a balance to be struck between the size, weight, cost and performance of the turbines. The length of the blades is limited, in part, by their mass, stiffness and their resistance to fatigue: all leading to a strong lightweighting trend and materials requirements that make carbon composites an attractive materials choice.

Williams Advanced Engineering is currently involved in developing a novel wind turbine blade design, which features a rigid spine with a flexible textile covering. The Racetrak™ process is being used to create a series of ribs that will sit along the main spar, giving the blade its aerodynamic profile. In addition to the excellent mechanical properties of the finished parts, the inherent flexibility of this process allows the engineers to subtly vary the rib geometry along the length of the blade using relatively soft tooling to generate further savings.

SUMMARY AND CONCLUSION

Using 223™ and Racetrak, Williams Advanced Engineering has the ability to bring lightweight composites into applications where the material cost and high cycle times associated with traditional manufacturing techniques has made these exceptional materials prohibitively expensive. While adoption is likely to be initially driven by the growing need to reduce weight, the new Williams processes also offer opportunities for innovative design to reduce complexity by integrating multiple components and to add additional value to the vehicle by embedding electronics that facilitate new functions.

These innovations will help to enable emerging technologies in the automotive industry such as electrification and automated driving. They also tap into a wider requirement for affordable composites in other industries where efficiency and environmental performance are increasingly important.

Looking beyond product benefits, 223™ and Racetrak™ also address two other areas of performance that are increasingly important to many industries: the growing need for end-of-life recovery and for low lifecycle emissions. The Williams approach addresses both issues: manufacturing can now use a very high proportion of end-of-life carbon recyclate and the CO_2 whole life emissions of carbon is inherently substantially lower than either aluminium or steel, the manufacture and re-use of which require high-energy processes.

“Both 223™ and Racetrak™ have the potential to be disruptive technologies, providing solutions to the obstacles that have so far prevented the volume adoption of carbon fibre,” concludes Williams Advanced Engineering Technical Director Paul McNamara. “These are the first internally-generated

Intellectual Property discoveries that we are bringing to market ourselves, and both are outstanding examples of the inspired thinking that Williams Advanced Engineering is applying to deliver advanced engineering for a sustainable future."

Williams Advanced Engineering believes both processes could be in volume production with a fully validated component by 2021.

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